On the Quantum Mechanical Wave Function as a Link Between Cognition and the Physical World: A Role for Psychology

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ABSTRACT

A straightforward explanation of fundamental tenets of quantum mechanics concerning the wave function results in the thesis that the quantum mechanical wave function is a link between human cognition and the physical world. The reticence on the part of physicists to adopt this thesis is discussed. A comparison is made to the behaviorists' consideration of mind, and the historical roots of how the problem concerning the quantum mechanical wave function arose are discussed. The basis for an empirical demonstration that the wave function is a link between human cognition and the physical world is provided through developing an experiment using methodology from psychology and physics. Based on research in psychology and physics that relied on this methodology, it is likely that Einstein, Podolsky, and Rosen's theoretical result that mutually exclusive wave functions can simultaneously apply to the same concrete physical circumstances can be implemented on an empirical level.

TEXT

It has been argued that the quantum mechanical wave function is a link between cognition and the physical world (Snyder, 1986, 1989, 1990). It is difficult to believe that the wave function in quantum mechanics could be such a link. But the use of experimental results from psychology provides an avenue to demonstrate that this thesis is correct. In the process, it is shown that the split that occurred between psychology and the physical sciences after the establishment of psychology as an independent discipline contributed to the delay in acknowledging this thesis.

It is the quantum mechanical wave function that gave rise to Einstein's comment (1949/1969) considering the possibility, which he found untenable, of "telepathically" (p. 85) changing the physical world in a gedankenexperiment that he proposed with Podolsky and Rosen (Einstein, Podolsky, & Rosen, 1935). Physicists have, in general, not accepted that the quantum mechanical wave function serves as a link between cognition and the physical world even though this thesis is the result of a straightforward explanation of the quantum mechanical wave function. Instead, they have opted either for a more complicated explanation that agrees with the predictions of quantum mechanics, involving hidden variables that would restore a classical-like structure to the physical world, or they have opted to accept the validity of quantum mechanical prediction while leaving out any view regarding the ontological implications of quantum mechanics.[1] It should be noted that there is no such reticence on the part of most physicists to accept the realistic view of the world implied by Newtonian mechanics. As Einstein (1949/1969) wrote in his "Autobiographical Notes":

> Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed. In this sense one speaks of "physical reality." In pre-quantum physics there was no doubt as to how this was to be understood. In Newton's theory reality was determined by a material point in space and time [functioning in a deterministic manner independent of cognition]; in Maxwell's theory, by the field in space and time. (pp. 81, 83)

Yet the thesis that the quantum mechanical wave function links cognition and the physical world is based essentially on the generally accepted view of quantum mechanics today by physicists. Two features of the quantum mechanical wave function that lead to this thesis and which are generally accepted by physicists are:

1) the wave function is the basis for probabilistic predictions concerning the physical existent described by the wave function (originally proposed by Born [1926/1983]), and

2) the in general change of the wave function immediately throughout space upon the observation of a quantity of the existent described by the wave function.

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[1] Mermin (1985) put the matter this way:

> Contemporary physicists come in two varieties. Type 1 physicists are bothered by EPR [the Einstein-Podolsky-Rosen gedankenexperiment] and Bell's theorem [an elucidation of this gedankenexperiment]. Type 2 (the majority) are not, but one has to distinguish two subvarieties. Type 2a physicists explain why they are not bothered. Their explanations tend either to miss the point entirely...or to contain physical assertions that can be shown to be false [i.e., they incorporate some form of hidden variables]. Type 2b are not bothered and refuse to explain why [even though they accept the validity of quantum mechanical prediction]. (p. 41)

To these features should be added the point that in quantum mechanics the wave function associated with a physical existent is the basis for whatever can be known concerning that physical existent (Liboff, 1992).[2]

These particular features are noted because they form the conceptual foundation for the Schrödinger cat gedankenexperiment, a thought experiment that provides an unusual result from a classical standpoint and which provides the basis for the suggested role of the wave function as a link between cognition and the physical world. The result of the Schrödinger cat gedankenexperiment, nonetheless, is interpreted by most physicists as not indicating that the wave function is a link between cognition and the physical world.

The discussion of this gedankenexperiment by a contemporary physicist, Shimony, who is also a philosopher of science will demonstrate the way in which physicists generally consider the nature of quantum mechanical wave function. Then Einstein's view on the issue will be presented. The application of experimental methodology and results from psychology in an investigation concerning spin angular momentum will provide additional support for the thesis that the quantum mechanical wave function (perhaps more accurately, the wave described by the wave function) is in part cognitive as well as physical. Finally, how physicists have not seen that psychological phenomena are part and parcel of the quantum mechanical wave function is explored.

THE SCHRÖDINGER CAT GEDANKENEXPERIMENT

Schrödinger (1935/1983) presented his cat gedankenexperiment in a paper that was written in response to the paper noted above by Einstein, Podolsky, and Rosen (1935). He wrote:

> A cat is penned up in a steel chamber, along with the following

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[2] Another interesting feature is that an arbitrary phase factor, $e^{i\alpha}$ where is any real number, can be associated with a quantum mechanical wave function that does not change the probabilities concerning the results of measurement events on the physical existent associated with this wave function. Liboff (1992) wrote:

> A wavefunction is determined only to within a constant phase factor of the form $e^{i\alpha}$. Although associated with all wavefunctions, this arbitrary quality has no effect upon any physical results. (p. 93)

(This arbitrary phase factor is not a phase factor such as that is a component wave function of a composite wave function. Rather it applies to the entire wave function, including space and time components.) Thus, the particular wave function associated with the physical existent is not unique. Indeed, there are an infinite number of particular wave functions, each having a different arbitrary phase factor, that can be associated with a physical existent.

> diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The Ψ-function of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.
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> It is typical of these cases [of which the foregoing example is one] that an indeterminancy originally restricted to the atomic domain becomes transformed into macroscopic indeterminancy, which can then be resolved by direct observation. (p. 157)

Shimony (1988) presented his abbreviated version of Schrödinger's gedankenexperiment as follows:

> A photon impinges on a half-silvered mirror. The photon has a probability of one-half of passing through the mirror and a probability of one-half of being reflected. If the photon passes through the mirror, it is detected, and the detection actuates a device that breaks a bottle of cyanide, which in turn kills a cat in a box. It cannot be determined whether the cat is dead or alive until the box is opened. (p. 52)

Then Shimony wrote concerning the gedankenexperiment:

> There would be nothing paradoxical in this state of affairs if the passage of the photon through the mirror were objectively definite but merely unknown prior to observation. The passage of the photon is, however, objectively indefinite, and so is the aliveness of the cat. In other words, the cat is suspended between life and death until it is observed. The conclusion is paradoxical, but at least it concerns only the results of a thought experiment. (p. 52)

It should be noted that Shimony incorrectly noted the gedankenexperiment he presented was indeed the Schrödinger cat gedankenexperiment. It is not, as Schrödinger relied on radioactive decay as his quantum mechanical phenomenon instead of the passage of a light photon through a mirror.

The two features of the quantum mechanical wave function noted earlier can be seen readily in the cat gedankenexperiment. Consider Shimony's version. The wave function that describes the photon in Shimony's version yields a probabilistic prediction concerning its passage through the mirror. Upon observation of the cat, which serves as the macroscopic measuring instrument, the wave function describing the photon changes to one that allows that the photon went through the mirror or one that allows that the photon did not go through the mirror and was reflected. Note that Shimony does not specify how close the observer needs to be to the cat. The observer can, in principle, be at any distance from the cat, even across the universe, so long as the observer makes an observation regarding whether the cat is alive. (Indeed, the observer does not even have to observe the cat directly but can rely on another observer who has observed the cat.)

How does Shimony's version of the Schrödinger gedankenexperiment reflect the view of most physicists that the wave function is not a link between cognition and the physical world, in this case between the observer's perception and the cat? And how does the gedankenexperiment show that the nature of the wave function as suggested here is warranted?

It is a link because of the two features of the quantum mechanical wave function cited earlier, the first being that there is nothing in quantum mechanics other than the probabilistic predictions concerning the physical world, predictions that have been supported by empirical test. The second feature is that these probabilities in general change immediately throughout space upon observation of a quantity of the physical existent described by the wave function that gives rise to the probabilistic predictions.

In a related vein, Shimony did not explicitly discuss the role and significance of the person as observer in the measurement process in quantum mechanics. Shimony, like many physicists, used the term *observation* ambiguously. Changing the latter quote from Shimony's paper to indicate that the concern specifically is with a *person* making the observation does not lessen the statement's validity:

> There would be nothing paradoxical in this state of affairs [concerning whether or not the cat is alive or dead before it is

> observed] if the passage of the photon through the mirror were objectively definite but merely unknown prior to observation [by a person]. The passage of the photon is, however, objectively indefinite, and so is the aliveness of the cat. In other words, the cat is suspended between life and death until it is observed [by a person]. The conclusion is paradoxical, but at least it concerns only the results of a thought experiment. (Shimony, 1988, p. 52)

Thus, in a circumstance where the observer is specified to be a person, the change in the wave function is most naturally thought of as tied to the perception of the human observer of the cat. The same point holds, though, for those circumstances where a macroscopic measuring instrument intervenes between a quantum mechanical phenomenon that is in essence probabilistic in nature. It is a human observer who ultimately records the result of any observation. Indeed, the cat gedankenexperiment represents this situation as the cat acts as a macroscopic measuring instrument and is also characterized by the same probabilities as the microscopic physical phenomenon (i.e., the photon) until a human observer makes his or her own observation of the cat. (It has been discussed elsewhere how observation in quantum mechanics necessarily means observation by a person, and in fact implies conscious observation by a person [Snyder, 1989, 1990]).

After presenting his version of the Schrödinger gedankenexperiment, Shimony discussed recent research that supports the thesis that it is specifically the person as observer that is central to quantum mechanical measurement. Shimony continued:

> It is now more difficult to dismiss the paradoxical nature of the conclusion [that the cat is neither dead nor alive until an observation of it is made], because something similar to Schrödinger's thought experiment has recently been achieved by a number of groups of investigators. (p. 52)

Shimony went on to describe this work that involves the magnetic flux through an almost closed superconducting ring, but in which the ends of the ring are separated by a thin slice of insulating material called a Josephson junction. An electric current can circulate through the ring with electricity passing through the Josephson junction in the quantum mechanical phenomenon called tunneling. The electric current produces a magnetic field. Associated with the component of the magnetic field perpendicular to the ring is the magnetic flux through the ring. For a uniform magnetic field, the value for the magnetic flux is the product of the the magnetic field component perpendicular to the plane through the superconducting ring multiplied by the area of the ring. As the electric current produces the magnetic field, and the electric current is comprised of a great many moving electrons (on the order of 10^{23}), the magnetic field can be considered a macroscopic phenomenon and the flux can be considered a macroscopic quantity characterizing the magnetic field.

Since it is a macroscopic quantity, the magnetic flux, in principle, does not require a macroscopic entity, such as the cat, to register the measurement result concerning a microscopic quantum mechanical existent so as to make the result available for observation. (In the Schrödinger gedankenexperiment, the microscopic existent is the small amount of radioactive material. In Shimony's version, it is the photon.) The magnetic field acts as both the radioactive material, or the photon, and as the cat in Schrödinger's gedankenexperiment and Shimony's version of it, respectively. As this magnetic flux is a quantity concerning a macroscopic physical existent, it is thus subject, in principle, to direct inspection by a human observer. In the research described by Shimony, the magnetic flux could have one of two values when measured. Though not allowed classically unless there is an external source of energy impacting the system, quantum mechanics allows for the spontaneous change in the values of the flux. This spontaneous change in the value of the flux depends on an indefiniteness in the flux prior to its being measured akin to the indefiniteness regarding whether or not the cat is alive in the Schrödinger gedankenexperiment prior to the cat's being observed.

Even though he cited research indicating that a macroscopic measuring instrument is not necessary in quantum mechanics, Shimony, in line with most physicists, does not acknowledge the central role of the person as observer in the change in the wave function associated with the observed physical system that generally occurs when an observation is made. He concluded his discussion of the magnetic flux through an almost closed superconducting ring by writing:

> Some students of the subject [quantum measurement theory] (including me) believe new physical principles must be discovered before we can understand the peculiar kind of irreversibility that occurs when an indefinite observable becomes definite in the course of a measurement. (p. 53)

By not acknowledging the role of the human observer in the change in the wave function that generally occurs when an observation is made, even in his discussion of research in which the cat in Schrödinger's gedankenexperiment is essentially taken out as an intermediate macroscopic measuring instrument, Shimony does not fully acknowledge the probabilistic basis of quantum mechanics. In terms of theoretical consistency and simplicity, acknowledging that quantum mechanics is fundamentally probabilistic in nature would only confirm what is accepted on a practical level by most physicists already. This fundamentally probabilistic nature indicates that quantum mechanics is concerned first with knowledge. As Liboff (1992) noted, with the development of quantum mechanics, "At the very core of natural law lay subjective probability - not objective determinism [that characterized Newtonian mechanics]" (p. 28). Thus, it really is not so surprising that human observation is also central to the nature of the wave function.

Shimony's acceptance on a practical level of the probabilistic nature of the wave function and the thesis that it in general changes upon observation of the existent with which it is associated is representative of most physicists. So is Shimony's reticence to accept on a fundamental level the straightforward explanation of these features of quantum mechanics. In portraying the cat gedankenexperiment, Shimony acknowledged that quantum mechanics accurately describes what is occurring in this gedankenexperiment. It is through the theory of quantum mechanics, and specifically the quantum mechanical wave function, that the cat has an indefinite status regarding whether it is alive which can be resolved only be an observation.

Without adopting this structure of the gedankenexperiment, Shimony would not be presented with the scenario to which he subsequently expressed reservations. He would not have been able to conclude his discussion of the cat gedankenexperiment by writing that the new principles he believed "must be discovered" (p. 53) would still have to account for "the peculiar kind of irreversibility that occurs when an *indefinite* [emphasis added] observable *becomes definite* [emphasis added] in the course of a measurement" (p. 53). The concept of an indefinite observable occurs in the theory of quantum mechanics, and the observable's taking on a definite value occurs in the course of a measurement in the theory of quantum mechanics. Essentially, Shimony maintained that some type of classical physical process will account for what are uniquely quantum mechanical phenomena.

EINSTEIN'S VIEW OF THE QUANTUM MECHANICAL WAVE FUNCTION

Einstein's view of the quantum mechanical wave function essentially follows the same analysis described by Shimony for the Schrödinger cat gedankenexperiment. After noting that Newtonian mechanics was readily understood in terms of the realistic basis of physics in the quote presented at the beginning of the paper, Einstein (1949/1969) continued:

> Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed. In this sense one speaks of "physical reality." In pre-quantum physics there was no doubt as to how this was to be understood. In Newton's theory reality was determined by a material point in space and time [functioning in a deterministic manner independent of cognition]; in Maxwell's theory, by the field in space and time. In quantum mechanics it is not so easily seen [i.e., the realistic basis of physics]. If one asks: does a Ψ-function of the quantum theory represent a real factual system of points or of an electromagnetic field, one hesitates to reply with a simple "yes" or "no"; why? What the Ψ-function (at a definite time) asserts, is this: What is the probability for finding a definite physical magnitude q (or p) in a definitely given interval, if I measure it at time t? [This is feature 1 of the quantum mechanical wave function noted above.] The probability is here to be viewed as an empirically determinable, and therefore certainly as a "real" quantity which I may determine if I create the same Ψ-function very often and perform a q-measurement each time. But what about the single measured value of q? Did the respective individual system have this q-value even before the measurement? To this question there is no definite answer within the framework of the [existing] theory, since the measurement is a process which implies a finite disturbance of the system from the outside [with the change in wave function, feature 2, the chief consequence of this finite disturbance this is feature 2 of the quantum mechanical wave function noted above]; it would therefore be thinkable that the system obtains a definite numerical value for q (or p), i.e., the measured

> numerical value, only through the measurement itself. (p. 83)[3]

Then Einstein presented the essence of a gedankenexperiment that he had proposed earlier with Podolsky and Rosen (Einstein, Podolsky, & Rosen, 1935).

> We now present the following instance: There is to be a system which at the time *t* of our observation consists of two partial systems S_1 and S_2, which at this time are spatially separated and (in the sense of the classical physics) are without significant reciprocity. The total system is to be completely described through a known Ψ-function Ψ_{12} in the sense of quantum mechanics. All quantum theoreticians now agree upon the following: If I make a complete measurement of S_1, I get from the results of the measurement and from Ψ_{12} an entirely definite Ψ-function Ψ_2 of the system S_2. The character of Ψ_2 then depends upon *what kind* of measurement I undertake on S_1.
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> Now it appears to me that one may speak of the real factual situation of the partial system S_2....On one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system S_2 is independent of what is done with the system S_1, which is spatially separated from the former. According to the type of measurement which I make of S_1, I get, however, a very different Ψ_2 for the second partial system (Ψ_2, Ψ_2^1,...). Now, however, the real situation of S_2 must be independent of what happens to S_1. For the same real situation of S_2 it is possible therefore to find, according to one's choice, different types of Ψ-function. (One can escape from this conclusion only by either assuming that the measurement of S_1 ((telepathically)) changes the real situation of S_2 or by denying independent real situations as such to things which are spatially separated from each other. Both alternatives appear to me entirely unacceptable.)
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> If now...physicists...accept this consideration as valid, then

3 The term "existing," along with the brackets that enclose it, that are found in the quote are actually part of the quoted material and not added by myself.

> B [a particular physicist] will have to give up his position that the Ψ-function constitutes a complete description of a real factual situation. For in this case [i.e., the case of a complete description] it would be impossible that two different types of Ψ-functions [representing mutually exclusive situations] could be co-ordinated [simultaneously] with the identical factual situation of S_2 [the same concrete physical circumstances]. (Einstein, 1949/1969, pp. 85, 87)

Bohr's (1935) response to Einstein, Podolsky, and Rosen's gedankenexperiment was that there is an unavoidable interaction between the physical existent measured and the measuring instrument in their gedankenexperiment that cannot be ignored. Essentially, Bohr's response was that the situation that Einstein, Podolsky, and Rosen were referring to is essentially quantum mechanical in its structure. That is, the structure of the gedankenexperiment presented by Einstein, Podolsky, and Rosen was based on: 1) probabilistic prediction rooted in the quantum mechanical wave function that describes the physical system, and 2) the in general immediate change throughout space of the wave function upon measurement of the physical system.

Furthermore, Bohr was saying that because the situation described by Einstein, Podolsky, and Rosen is framed within the theory of quantum mechanics, their result that two very different wave functions (really two mutually exclusive views of the world) can simultaneously characterize the same concrete physical circumstances simultaneously in quantum mechanics is incorrect.[4] According to Bohr, the particular interaction of the measuring apparatus and S_1 is associated with a specific state of S_2 upon the measurement

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[4] The wave functions can be considered to simultaneously characterize the same concrete physical circumstances, S_2, because:

(1) in quantum mechanics, there is no physical limitation in principle on the implementation of the particular measurement procedure used on S_2;

(2) the velocity limitation of the special theory precludes a physical existent from mediating the change in wave functions from Ψ_{12} for S_1 and S_2 before the measurement on S_1 to a specific wave function characterizing S_1 and a specific wave function characterizing S_2 after the measurement on S_1.

The instantaneous change in the wave function Ψ_{12} to the wave functions Ψ_1 for S_1 and Ψ_2 for S_2 throughout space when S_1 is measured falls outside the causal structure of spacetime in the special theory. This causal structure involving past and future is limited by the velocity of light in vacuum in an inertial reference frame.

of S_1. But Einstein, Podolsky, and Rosen's result is basically correct. Two very different wave functions can indeed simultaneously characterize the same concrete physical circumstances, even if the state of S_2 depends on the measurement result at S_1. As noted in feature 2 of the quantum mechanical wave function, a change in wave function upon measurement of the physical entity with which it is associated occurs immediately throughout space.

Where Bohr was correct was in noting that their conception of physical reality that "physics is an attempt conceptually to grasp reality as it is thought independently of its being observed" (Einstein, 1949/1969, pp. 81) is not part of quantum mechanics. And it is quantum mechanics that they used to structure their gedankenexperiment. In not allowing for the interaction between the physical existent measured and the measuring process of which the observer is the chief component in defining an element of physical reality, they were able to frame their argument so that the result was that quantum mechanics is not a complete theory of the physical world. Thus, Bohr was correct in his criticism up to a point, and Einstein, Podolsky, and Rosen were correct without the artificial constraint of their realistic definition of the physical world and its essential independence of the physical theory describing it.

THE BEHAVIORISTS

Physicists implementing the experimental conditions noted by Einstein, Podolsky, and Rosen have been able to go a long way toward realizing their theoretical result concerning the possibility of simultaneous mutually exclusive situations characterizing the same concrete physical circumstances. The work of Aspect, Dalibard, and Roger (1982) and Aspect, Grangier, and Roger (1982) is an example. But they have not been able to fully implement this result. This is because physicists have focussed only on manipulating the physical circumstances which are concerned directly with the physical existent measured and the measuring instrument used to measure this existent (e.g., S_2) in implementing Einstein, Podolsky, and Rosen's result. That they have focussed only on these physical circumstances has allowed physicists to maintain that the condition of simultaneity of mutually exclusive situations for the same concrete physical circumstances could not be met. Essentially, while this condition has not been met, physicists have maintained that a cognitive aspect of the result presented by Einstein, Podolsky, and Rosen, a result that is tied to the nature of the quantum mechanical wave function, could not be supported. The position of physicists as concerns quantum mechanics is similar to the position held by the behaviorists in psychology in the earlier part of the 1900's.

Throughout much of this century, behaviorism was the dominant theoretical model in American psychology. For a number of years, behaviorists conducted animal studies in extremely constrained experimental arrangements while testing a model of behavior that considered the mind to be essentially a relay station between incoming stimuli and bodily responses. Generally speaking, the connection between environmental stimuli and bodily responses depended on drive reduction (e.g., a decrease in hunger) where drive reduction was defined in terms of environmental variables (e.g., amount of time since last presentation of food). Hull's 1943 behavioral system is a case in point. Hilgard and Bower (1975) noted that for Hull, "Habit strength ($_{S}H_{R}$) [i.e., learning] is the result of a reinforcement of stimulus-response connections in accordance with their proximity to need [and drive] reduction" (p. 161).

Psychologists conducted studies of learning where, for example, rats were placed in mazes with goal boxes and environmental variables, such as the quantity of food in the goal box, were manipulated to see their effect on the learned ability of rats to reach the goal box. In many studies conducted over a number of years, behaviorists found that the results of their experiments largely supported the major premise of their model, namely that learning could be understood as the effect of environmental stimuli or conditions on bodily responses. But even in these constrained experimental circumstances, animals showed evidence of cognitive activity, and eventually the data built to a point where the theoretical structure of the behaviorists could no longer support this data. For example, Tolman (1932/1949) reported studies by Blodgett (1929) and Tolman and Honzik (1930) who found that rats left to explore a maze in which no food was placed in the goal box reached the criterion for learning (e.g., time to reach the goal box) when trials were conducted with food in the goal box more quickly than rats who did not have a chance to explore the maze before these trials began.

In retrospect, it seems surprising that psychologists could hold with such conviction that the mind was nothing more than a relay mechanism and that they were unaware for the most part that the design of their experiments would tend to produce results that supported this theory. With physicists the circumstances are somewhat different, but the strong commitment to a particular view of the phenomena of their discipline, (i.e., physical phenomena) that excludes a straightforward approach to these phenomena is similar to the attitude of the behaviorists concerning learning. In addition, where physicists limit their manipulation of experimental variables to those affecting the physical existent measured and the measuring apparatus used in the measurement process, physicists are very much like the behaviorists in the earlier part of the 1900's. Physicists' choice of experimental arrangements serves to support their particular outlook on physical phenomena by limiting their research to those areas that will not explicitly indicate that their particular outlook is incorrect. As will be shown, there is another area where experimental variables can be manipulated. These are concerned with the act of observation. In the future, looking back on the present, it will appear surprising that physicists could hold on to their inconsistent view of the wave function in quantum mechanics for so long.

A Contribution from Psychology

It is possible to implement Einstein's result that two very different wave functions can simultaneously characterize the same concrete physical circumstances. And the manner in which it can be done only serves to emphasize that the wave function is a link between cognition and the physical world. It can be done through studying the act of observation in quantum mechanics, something that physicists have not done. Implementing Einstein's result relies on experimental work in psychology. This research involves the effects of altered incoming visual stimuli (i.e., light) on visual experience and visually guided behavior. Helmholtz, the physicist, was especially interested in this research direction during the formative years of psychology that culminated in the establishment of psychology as an independent discipline of study in the latter 1800's.

Helmholtz (1866/1925) reported a study in which a subject wore prisms that displaced objects, including his hand, that were in the field of view laterally from what would have been their normal position had the subject not worn the prisms. In the first instance, the subject's hand was not in view and the subject closed his eyes after having noted a particular object in his field of view. When he reached for the object, he missed it by reaching too far in the direction in which the prisms displaced the object. In reaching for an object, the subject was guided by the position of the object he had seen through the prisms. Repeated trials for the subject using the same method, or sometimes by quickly touching an object with one's hand while viewing this process through the prisms, resulted in the subject correctly touching the designated object when the subject's eyes were closed. After showing adaptation in this reaching behavior while wearing the prisms, repeating this method with the prisms removed, the subject erred in reaching for a designated object in the opposite lateral direction to that in which he original erred that occurred when the prisms were worn. Repeated trials corrected these errors for the subject no longer wearing the prisms.[5]

The specific research direction of concern in this paper involves investigating the effects of a particular type of alteration of incoming visual stimuli on visual experience and visually guided behavior. This research direction is concerned with the inversion of visual stimuli on the retina. When light enters the eye, it is reflected across both the horizontal and vertical that divide the top and lower halves, as well as the right and left halveshemifields, of the visual field. The incoming visual stimuli are up-down reversed and right-left reversed (Dolezal, 1982; Kandel, Schwartz, & Jessell, 1991). (In the context of this paper, unless more precisely specified, the terms "inversion" and "inverted" will refer to either rotation of the incoming light 180^{o} around the line of sight, or the reflection [or flipping] of incoming light between the top and lower halves of the visual field along the horizontal separating them.) In the late 1800's, Stratton, a professor of psychology at Berkeley, (1896, 1897a, 1897b) conducted two very interesting experiments in the very late 1800's. Stratton investigated the effects on visual experience of rotating the incoming visual stimuli 180^{o} around the line of sight such that the retinal images were right side up instead of being in their customary inverted orientation. Stratton's results were remarkable. In commenting on the earlier experiment, he wrote:

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[5] The experiment is presented by Helmholtz as follows:

> Take two glass prisms with refracting angles of about 16^{o} and 18^{o}, and place them in a spectacle frame, with their edges both turned toward the left. As seen through these glasses, the objects in the field of view will all apparently be shifted to the left of their real positions. At first, without bringing the hand into the field, look closely at some definite object within reach; and then close the eyes, and try to touch the object with the forefinger. The usual result will be to miss it by thrusting the hand too far to the left. But after trying for some little while, or, more quickly still, by inserting the hand in the field and, under the guidance of the eye, touching the objects with it for an instant, then on trying the above experiment again, we shall discover that now we do not miss the objects, but feel for them correctly. It is the same way when new objects are substituted for those with which we have become familiar. Having learned how to do this, suppose now we take off the prisms and remove the hand from the field of view, and then, after gazing steadily at some object, close our eyes and try to take hold of it. We find then that the hand will miss the object by being thrust too far to the right; until after several failures, our judgment of the direction of the eyes is rectified again. (Helmholtz, 1866/1925, p. 246)

> In fact, the difficulty of seeing things upright by means of upright retinal images seems to consist solely in the resistance offered by the long-established experience. There is certainly no peculiar inherent difficulty arising from the new conditions themselves. If no previous experience had been stored up to stand in opposition to the new perceptions, it would be absurd to suppose that the visual perceptions in such a case would seem inverted. Any visual field in which the relations of the seen parts to one another would always correspond to the relations found by touch and muscular movement would give us 'upright' vision, whether the optic image lay upright, inverted, or at any intermediate angle whatever on the retina. (Stratton, 1896, p. 617)

His comments apply as well to the results of the second, more thorough experiment. In his report on the second experiment, he wrote:

> The inverted position of the retinal image is, therefore, not essential to 'upright vision,' for it is not essential to a harmony between touch and sight, which, in the final analysis, is the real meaning of upright vision. For some visual objects may be inverted with respect to other visual objects, but the whole system of visual objects can never by itself be either inverted or upright. It could be inverted or upright only with respect to certain non-visual experiences with which I might compare my visual system--in other words, with respect to my tactual or motor perceptions. (Stratton, 1897b, pp. 475-476)

Subsequent work by other researchers in which all incoming visual stimuli were rotated 180° around the line of sight (e.g., Ewert, 1930; Snyder & Pronko, 1952) or up-down reversed (the top and bottom halves of the visual field are reversed) (e.g., Dolezal, 1982; Kohler, 1962, 1964) has for the most part, if not entirely, provided substantial support for Stratton's finding concerning the relative nature of upright vision. The research indicates that there is a high degree of flexibility of the visual system with regard to inversion of incoming visual stimulation on the retina, including that an observer subject to such reversal quickly regains very significant competency in interacting with the environment.

For example, Snyder and Pronko (1952) found in their study:

> During the 30-day period that the inverting lenses were worn, the visuo-motor coordinations were refashioned so that the subject performed even better than before the lenses were put on....Introducing the inverted visual field for 30 days and subsequent "normalization" (lenses removed), [sic] modified the learning situation. However, the subject went on learning despite these disrupting factors (p. 166).

In general, visual experience restabilizes quickly considering the relatively very brief period of time that the visual stimuli are reversed compared to the subjects' life experiences prior to their participation in one of the experiments.

In the laboratory, competency on sensorimotor tasks developed with unrotated light has been shown to transfer to circumstances where incoming light is rotated 180^{o} (Ewert, 1930; Snyder & Pronko, 1952). Furthermore, increased competency on the same sensorimotor tasks subsequently developed with rotated light has been shown to transfer to circumstances where the incoming light is no longer rotated 180^{o} (Ewert, 1930; Snyder & Pronko, 1952). The learning curve for these sensorimotor tasks was in general fairly smooth, except for a spike when the incoming visual stimuli were first rotated 180^{o} around the line of sight. In natural settings, individuals wearing some form of optical apparatus that inverted incoming visual stimuli have reported such activities as driving an automobile, riding a motorcycle, or riding a bicycle with a significant degree of skill within a relatively short time of putting on the apparatus for the first time (Dolezal, 1982; Kohler, 1962). Research has indicated that after a relatively brief period of time exposed to inverted visual stimuli, visual experience in general appears normal and as this normal visual experience exists in conjunction with the recaptured competency of the individual in the environment, the visual field is upright in the same way that it was upright before the incoming visual stimuli were reversed (Dolezal, 1982; Kohler, 1962, 1964; Snyder & Pronko, 1952).

In a related study, Brown (1928) wore goggles with prisms that rotated incoming light 75^{o} around the line of sight for one week, and he demonstrated a significant degree of adaptation to this rotation. This occurred even though he described his apparatus as "too unwieldy" (p. 134) to wear every night on a one-half mile trip to his university where various tests were run. Other work investigating adaptation of the visual system to alterations in incoming visual stimuli have also indicated a very high degree of flexibility in the operation of the visual system (e.g., Gibson, 1933; Held, 1965; Held & Freedman, 1963).

Ewert (1930) and Munn (1955/1965), one of Ewert's subjects in his experiment with rotated visual stimuli, have disputed the finding that visual experience becomes upright and, in general, normal after some experience with rotated incoming visual stimuli. It should be noted, though, that the major concern of Ewert and Munn is not so much the subject's phenomenal experience with rotated light but rather with the interpretation of what this phenomenal experience means. For example, Munn (1955/1965) wrote:

> Localizing reactions became so automatic at times that a 'feeling of normalcy' was present. This is probably the feeling reported by Stratton and interpreted as "seeing right-side up." (p. 293)

Or, Ewert concluded that:

> In all forms of activity where overt localizing responses are present there is rapid adjustment to the distracting visual interference until at the end of 14 days of practice the interference is entirely overcome in some of the activities investigated and almost overcome in the other forms....Constant interference during visual disorientation does not prevent the steady growth of a habit. (Ewert, 1930, pp. 353, 357)

Snyder and Pronko (1952) performed an experiment similar in many respects to Ewert's. Munn wrote about Snyder and Pronko's work: "The results were essentially like his [Ewert's]" (p. 294). In contrast to Ewert, Snyder and Pronko concluded:

> It appears that perceivings form a behavior sequence going back into the individual's past. If the subject of the present experiment had always worn the inverting lenses, his past perceivings would have been of a piece with those of the moment when the question ["Well, how do things look to you? Are they upside-down?" (p. 113)] was directed at him. Obviously, then, they would not have been in contrast with the latter and would not have called attention to themselves. Stated in another way, if this subject had somehow developed amnesia at the point at which he put on the inverting lenses, then things could not appear upside-down because there would be no basis of comparison or contrast. That they did appear upside-down is clearly a strict function of his previously acquired perceivings. (pp. 113-114)

In *A History of Experimental Psychology*, Boring (1929/1950) wrote about Stratton's work:

> In 1896 Stratton put the matter to test, having his subjects [actually only Stratton himself] wear a system of lenses which reversed the retinal image and made it right side up. The expected happened. The perceived world looked upside down for a time and then became reversed. Taking the glasses off resulted once again in reversal which was soon corrected. Stratton was not, however, confused by the homunculus. He described how up was nothing in the visual sensory pattern other than the opposite of down, and that orientation is achieved by the relation of the visual pattern to somothesis and behavior. When you reach up to get an object imaged at the top of the retina, then you have indeed got the visual field reversed and will not find the object unless you have on Stratton's lenses. Ewert repeated this experiment in 1930, with similar results....Had the view of a freely perceiving agent in the brain not been so strongly entrenched, this problem could not have continued to seem so important in 1604, 1691, 1709, 1838, 1896 and 1930 [1930 being the year that Ewert reported his experimental findings]. (p. 678)

Boring knew of Ewert's work and saw that the empirical results obtained by Ewert supported Stratton's conclusion even if Ewert's own conclusion based on the empirical results he found were not in agreement with Stratton's conclusions. Boring saw that Ewert's experimental results did not seriously challenge Stratton's work. Dolezal (1982) wrote concerning the results of his experiment and those found in other experiments:

> In the course of living in a world transformed, the observer's initial fears become calmed, he or she finds the discomforts quite tolerable, the strange sights fade and become common, and ineptness changes to competency. (p. 301)

In sum, research has shown that in inversion of visual stimuli on the retina, a sense of normalcy returns to a significant degree to visual experience accompanied by a return to high levels of competency in visually guided behavior. Both of these events support Stratton's conclusion that upright vision returns after an individual gains experience in the world with inverted visual stimuli.

A Biperceptual Capability

Dolezal has proposed that the observer who adapts to inversion of incoming visual stimuli is biperceptual and biperformatory. Biperceptual refers to the simultaneous existence of the visual perceptual capabilities associated with both pre-inversion and post-inversion conditions. Yet these capabilities are also divided into distinct reference frames for the individual who has undergone inversion of incoming visual stimuli. Similarly, biperformatory refers to the simultaneous existence of an individual's capabilities to act competently in the environment both before and after inversion of the incoming visual stimuli. Yet these capabilities are divided into distinct areas for the individual who has experienced and adapted to this inversion of incoming visual stimuli. Dolezal (1982) wrote:

> The adapted observer appears to differ from the unadapted observer in several main respects. After some 200 hours of living with reversing prisms, an observer once again experiences visual stability of the perturbed environment [i.e., up-down reversal of incoming visual stimuli]. This is true for a wide range of rates of head movements (HMs). Moreover, the adapted observer has acquired what may be called another "personality" (i.e., he or she has the dual facility to be perceptually and emotionally comfortable and to act competently both with and without transforming prisms). The adapted observer is thus a very different creature from the unadapted observer--somewhat like someone with a second language or a novel set of skills that can only be directly displayed under special circumstances (cf. state-dependent learning and recall). The observer becomes what I call *biperceptual* and *biperformatory*....In general, the adapted observer is capable of living in both worlds, under both sets of information conditions and behavioral requirements with roughly equal comfort and competence. (p. 297)

Dolezal discussed some anecdotal evidence from his own experience to support his thesis of biperceptual and biperformatory capabilities. For example, if there were not some memory specifically associated with learning while wearing up-down reversing prisms that remained accessible after the experiment was completed, then how did Dolezal have an immediate sense of familiarity with a particular scene when donning the prisms a year after the experiment was completed? Or, if the memory was not tied specifically to his experience while wearing the reversing prisms, why would Dolezal find it difficult to recognize an individual after the experiment that he had only seen prior to that time while wearing the reversing prisms?

Consider the following observation reported by the subject in Snyder and Pronko's study, who happened to be Snyder:

> Toward the end of the experiment [i.e., the period in which the subject wore the inverting glasses], the subject was adequately adjusted [adapted]. The following insightful experience occurred. He was observing the scene from a tall building. Suddenly someone asked, "Well, how do things look to you? Are they upside-down?"
>
> The subject replied, "I wish you hadn't asked me. Things were all right until you popped the question at me. Now, when I recall how they *did* look *before* I put on these lenses, I must answer that they do look upside down *now*. But until the moment that you asked me I was absolutely unaware of it and hadn't given a thought to the question of whether things were right-side-up or upside-down." (Snyder & Pronko, 1952, p. 113).

In a study of retention of the effects of such inversion, Snyder and Snyder (1957) found that when the inverted conditions are re-introduced for a subject some time after the subject's initial experience with inverted visual stimuli, the subject's adjustment the second time to the inverted visual stimuli indicated that learning occurred as a result of the first experience and had been retained over a two-year period between the first and second experiences with inversion of the incoming visual stimuli. Specifically, they found that the time to complete various tasks consistently took less time to complete in the second experience than in the first experience. The learning curves in the first and second experiences were very similar for each of the tasks, only in the second exposure the times to complete the tasks were consistently lower than the times to complete the tasks in the first exposure.

In his research, Stratton noted how quickly visual and other perceptions and images could switch quickly from those characterizing experience while wearing the inverting optical apparatus to those perceptions and images characterizing experience before Stratton wore his optical apparatus. He also noted the possibility of their coexistence. For example, on the seventh day of wearing his apparatus in the second experiment, Stratton (1897b) wrote:

> When I watched one of my limbs in motion, no involuntary suggestion arose that it was in any other place or moved in any other direction than as sight actually reported it, except that in moving my arm a slightly discordant group of sensations came from my unseen shoulder. If, while looking at the member, I summoned an image of it in its old position, then I could feel the limb there too. But this latter was a relatively weak affair, and cost effort. When I looked away from it, however, I involuntarily felt it in its pre-experimental position, although at the same time conscious of a solicitation to feel it in its new position. This representation of the moving part in terms of the new vision waxed and waned in strength, so that it was sometimes more vivid than the old, and sometimes even completely overshadowed it. (p. 465)

It is remarkable that the visual system has demonstrated a great degree of flexibility in the inversion experiments given the degree of artificiality introduced into the experimental circumstances by the optical apparatus that have been used. For example, Stratton used a device that allowed for incoming light to only one eye while the other eye was covered over the time Stratton wore the device. Ewert's device was lightweight but allowed for a limited visual field. In an attempt to widen the visual field over that of most other experiments in which all of incoming stimuli are reversed for an extended period of time, Dolezal (1982) built his optical device out of a *football helmet* in which glass prisms were inserted in the limited space usually left open for a football player to see. His device weighed *8 pounds, 6 ounces*. There is further work to be done in this area of the effect of inverted visual stimuli on visual experience and visually guided action. But the basic result that there is significant adaptation in visual experience and visually guided action to inversion of incoming visual stimuli has been established.[6]

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[6] One avenue for further work is suggested by anecdotal evidence developed using the recently developed technique of functional magnetic resonance imaging that changes in visual experience resulting from a rotation of the incoming visual stimuli on the retina are reflected in neurophysiological processes. (Anecdotal evidence is all that is available at the present time.) In an experiment that employed this technique, subjects wore glasses that divided their visual fields so an eye would see only half its usual stimuli. The researcher, Schneider, found, "I was getting data on one person and it looked like his brain was upside down. I

Hard Wiring of the Visual System and the Isotropy of Space

Originally, Stratton was concerned with showing that two theories concerning inversion of incoming light were incorrect. Essentially, these theories maintained some sort of hard-wiring of either the neural component of the visual system (the projection theory) or its supporting musculature (the eye movement theory). In the projection theory, inversion of the retinal image was needed because of the crossing of the lines of direction of light from external objects when light from the external world moves through the eye. Perception of objects was considered to follow these lines of direction that projected outward to the upright objects in the physical world from which the light rays originated.

The eye movement theory related to the use of the musculature about the eye to provide definitive information about the correct position of the objects in the world. Thus, if the eyes move upward in their sockets, they see the upper parts of objects in the physical world that are before them, and if the eyes move

---

checked and rechecked the numbers wondering what the heck was going on. Then I found out he had put the glasses on wrong, so that his visual field was flipped upside down. I didn't know it at the time, but just by looking at this brain I could tell he was seeing upside down" (Blakeslee, 1993, p. B6). Thus, it is important to systematically investigate the initial neurophysiological representation of rotated visual stimuli as well as the later neurophysiological representation of these rotated visual stimuli.

It is predicted based on the anecdotal evidence that the rotation of the neurophysiological representation would be confirmed when the change in orientation of incoming light first occurs. Some time later, it is predicted that at least one element of the neurophysiological representation will revert to that which would occur if the incoming light had not been rotated. The latter prediction derives from the anecdotal evidence and the evidence of reorientation of visual experience to being upright after some time when the incoming stimuli are rotated 180^{o}. If the predictions are confirmed, the empirical evidence would lend support to the conclusions of previous work on the reorientation of visual stimuli on the retina that relied on behavioral and experiential evidence. These predictions, if confirmed, would also imply tremendous plasticity in neurological functioning. It was because of his hunch that there was great plasticity in neurological functioning that Stratton undertook his original research to see whether the projection theory of vision or the eye movement theory, both of which implied hard wiring of the visual system, would hold up to experimental scrutiny.

It is possible that this last suggested experimental modification could be explored in an animal study where degree of adaptation to rotation of incoming visual stimuli can be assessed behaviorally. Behavior and neurophysiological function could be studied to see if: 1) there is modification of the neurophysiological representation of the visual world that correlates with confused behavior upon an animal's wearing an optical apparatus that rotates incoming light, and 2) there is a return of the neurophysiological representation of the visual world to its pre-rotation status that correlates with regained behavioral competency when the apparatus is removed.

downward in their sockets, they see the lower part of these objects in the physical world that are before them. In this process, though, movement of the eye upward, for example, results in the lower portion of the retina receiving more of the incoming light. Inversion of the incoming light would correct this problem and would allow for eye movements to indicate the upright nature of the physical world.

Basically, physicists have held to the basic tenet behind the projection theory and the eye movement theory that there is only one way that the visual system can function in order that the physical world is perceived as upright. This is an assumption that Boring (1929/1950) maintained was inappropriate from 1604 and onward, and he maintained it was based on the notion of the homunculus. It can be seen in the descriptions provided of the projection theory and the eye movement theory that both theories carry another tenet as an assumption regarding the physical world. This tenet is that the physical world itself has an absolute status as regards its being upright. For example, if the physical world were indeed upside down, would scholars seriously entertain a theory of visual perception based on the hard wiring of the visual system? It should be noted that this tenet violates an extension of the concept of the isotropy of space in that the directions in space are not fundamentally alike.

ALTERING THE EXPERIMENTAL CIRCUMSTANCES WITHOUT CHANGING THE PHYSICAL SYSTEM OR THE APPARATUS USED TO MEASURE IT

It remains to show how this adaptability of visual experience and visually guided behavior to inversion of incoming visual stimuli allows Einstein, Podolsky, and Rosen's result concerning the simultaneous existence of mutually exclusive situations applied to the same concrete physical circumstances to be realized in an experiment.

Stratton's results, and those of other researchers following his general line of research, provide an avenue for demonstrating that mutually exclusive circumstances concerning the same concrete physical circumstances nonetheless may be simultaneously perceived in a uniform way. Essentially, this work has shown that though sensory data impinging on us may indeed be of fundamentally different forms, the perception associated with this data may be uniform. The work of Stratton and those who followed after him is not the only work to demonstrate this point. This point is at the heart of perceptual constancies. For example, though not concerned with mutually exclusive versions of reality, size constancy and shape constancy also indicate a uniformity of perception even though the associated sensory data impinging on us may vary widely in character.

Stratton's results are particularly relevant to the simultaneous, mutually exclusive situations allowed in quantum mechanics and provide the basis for an empirical test of them. Consider the spin angular momentum of an electron. It is possible to measure the component of this momentum along any one of three orthogonal axes, x, y, and z (three spatial axes all at right angles to one another). Assume in an idealized experiment that this measurement occurs from direct visual inspection of the electron in the following way. Through the use of a Stern-Gerlach apparatus (Eisberg & Resnick, 1985; Liboff, 1992), a nonuniform magnetic field oriented along the z axis is placed in the path of the electron, and the subject watches to see which way the electron moves in the field. (As discussed, the introduction of a macroscopic measuring device does not change the circumstances in any critical way.) Assume the z axis is in the vertical direction relative to the subject, appearing to go up and down. Assume that the y axis runs perpendicular to the ideal plane formed by the subject's face and that prior to entering the nonuniform magnetic field the electron is traveling along this axis. Assume that the x axis runs horizontally relative to the subject, from side to side. The experimental circumstances are depicted in Figure 1, where + and - refer to the positive and negative directions along a spatial axis.

According to quantum mechanics, precise knowledge resulting from measurement of one of these momentum components means that knowledge of each of the other two momentum components is completely uncertain. Precise knowledge of the component along the z axis, for example, means that knowledge of each of the components along the x and y axes is completely uncertain.

This limitation concerning the knowledge of certain paired quantities in quantum mechanics also characterizes the simultaneous precise determination of the position and momentum of an electron (Eisberg & Resnick, 1985; Liboff, 1992). Precise knowledge of the electron's momentum entails complete uncertainty regarding its position, and precise knowledge of its position entails

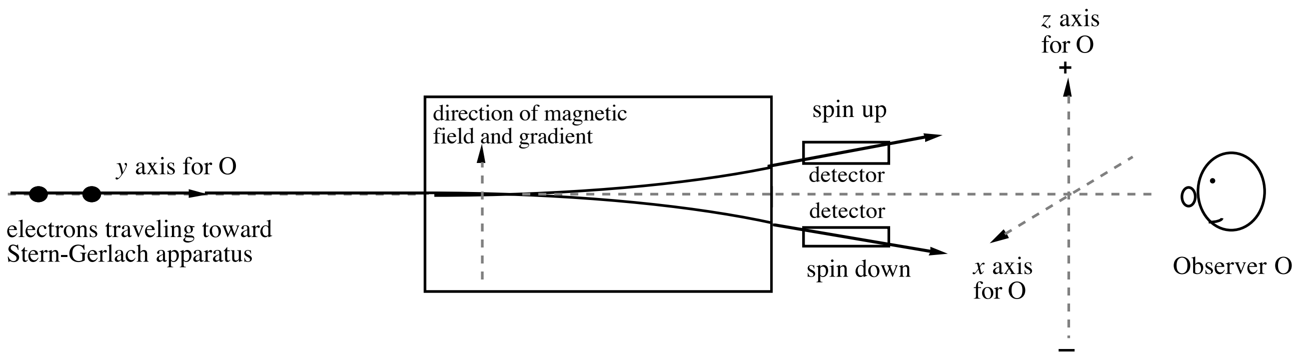

Figure 1

Observer O, not wearing the optical apparatus, viewing the spin component along the *z* axis in the spatial structure of O of electrons traveling through a Stern-Gerlach apparatus without rotation of the visual field.

complete uncertainty regarding its momentum. As Einstein, Podolsky, and Rosen (1935) wrote:

> It is shown in quantum mechanics that, if the operators corresponding to two physical quantities, say A and B, do not commute, that is, if $AB \neq BA$, then the precise knowledge of one of them precludes such a knowledge of the other. Furthermore, any attempt to determine the latter experimentally will alter the state of the system in such a way as to destroy the knowledge of the first. (p. 778)

Where A and B are the operators corresponding to the components of the position and momentum of an electron, respectively, along a particular spatial axis, they do not commute. Similarly, where A and B are the operators for any two components along orthogonal spatial axes of the spin angular momentum of an electron, they do not commute.

One can use an apparatus like that developed by Stratton to rotate the incoming light to an experimental subject such that the light is rotated around the y axis ninety degrees. Then, what was information concerning the z axis is now information concerning the x axis as concerns the light impinging on the subject's retina. Given Stratton's results, there is a good possibility that, after a period of orientation with this apparatus, particularly if it is worn for an uninterrupted period in the natural environment, the subject will see the electron moving up or down and not sideways.

Indeed, the natural scenarios tested by Stratton and others are potentially much more complex than the scenario that could be presented to an observer in a laboratory setting observing the path of an electron along a spatial axis in an inhomogenous magnetic field like that created by a Stern-Gerlach apparatus. It does appear that adaptation to inverted visual stimuli depends to a significant degree on a subject's experience in moving in his environment while incoming stimuli are inverted by the optical apparatus. Thus, the observer in the proposed experiment should continually wear the apparatus in the natural environment during waking hours. Because of the uncomplicated nature of the adaptation in the proposed experiment, though, a minimal amount of motor experience by the subject might be sufficient for the necesary degree of adaptation of the visual perceptual system to occur.

Once this degree of adaptation occurs in the subject's visual experience, according to the information impinging on the subject's retina, the subject is measuring what in the original situation without rotation of the incoming light is the x axis. What for observers in the original situation is up and down along the z axis is for the subject up and down along the x axis (Figure 2). For this subject, the spin components along the y and z axes are completely uncertain. Thus, it appears possible to have simultaneous, mutually exclusive situations involving the components of spin angular momentum of the electron along two orthogonal spatial axes. These situations do not exist for the same individual in this particular example, but nonetheless the example shows that, in a general way, simultaneous, mutually exclusive situations can occur.

Evidence supporting a biperceptual character of visual perception after adaptation to inversion of incoming visual stimuli has been noted. As discussed, this biperceptual character after adaptation concerns the simultaneous existence of the distinct visual perceptual capabilities associated with both pre-inversion and post-inversion conditions. It may indeed be possible for one subject in the experiment outlined above involving spin angular momentum components along orthogonal spatial axes to be involved in mutually exclusive situations simultaneously concerning the same concrete physical circumstances. That is, the adapted subject may be able to instantly shift from being involved in one of the experimental scenarios to the other.

There is another expression of simultaneous mutually exclusive situations besides that already discussed that is perhaps even more surprising. Consider that an optical apparatus is used that rotates incoming visual stimuli 180^{o} around the line of sight. For the subject wearing the device but not yet adapted, the negative direction of the z axis is associated with spin up and the positive direction of the z axis is associated with spin down. Once a significant degree of adaptation in the subject's visual experience occurs, when the subject observes that an electron has spin up in the positive direction of the z axis, according to the information impinging on the subject's retina the subject is measuring what in the original situation without rotation of the incoming light is spin up in the negative direction of the z axis. Similarly, when the subject observes that an electron has spin down in the negative direction of the z axis, according to the information impinging on the subject's retina the subject is measuring what in the original situation without rotation of the incoming light is spin down in the positive direction of the z axis (Figure 3).

If this result is considered in terms of the Schrödinger cat gedankenexperiment, it is as if in one situation, one atom of the radioactive material decayed leading to the cat being dead when observed, while

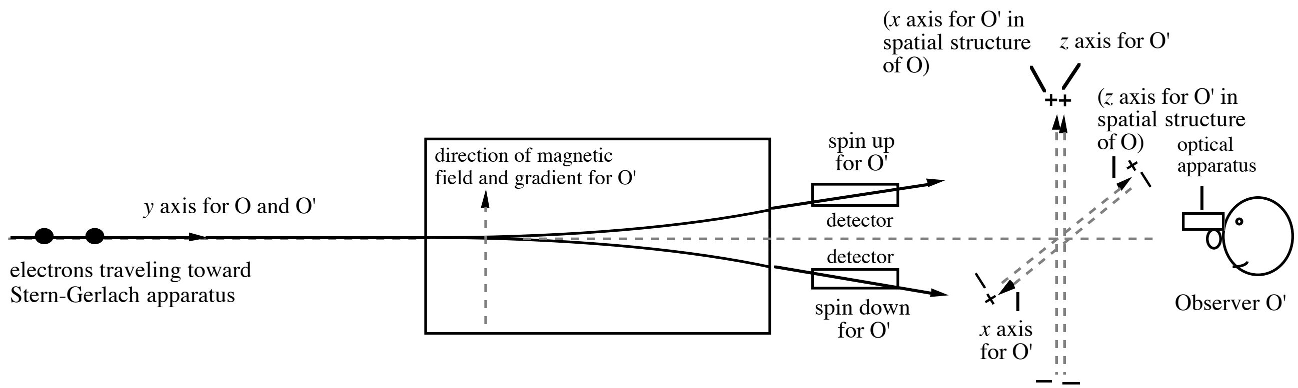

Figure 2

Observer O', adapted to wearing the optical apparatus, viewing the spin component along the *z* axis in the spatial structure of O' of electrons traveling through a Stern-Gerlach apparatus with 90 degree rotation of the visual field, in terms of the spatial structure of O, around the *y* axis. (*x* and *z* axes for O' in spatial structure of O, who does not wear the optical apparatus, are shown.)

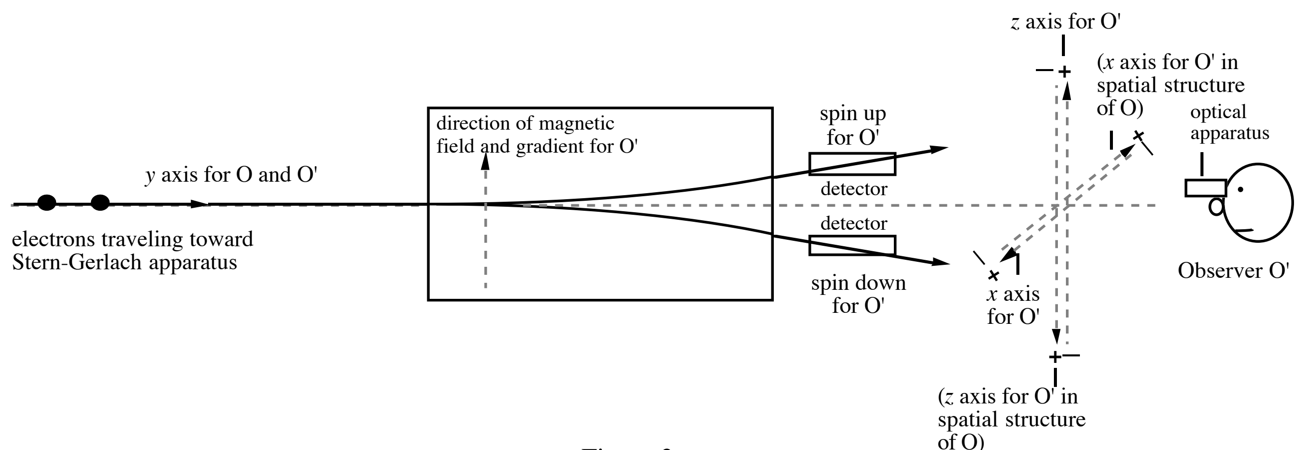

Figure 3

Observer O', adapted to wearing the optical apparatus, viewing the spin component along the *z* axis in the spatial structure of O' of electrons traveling through a Stern-Gerlach apparatus with 180 degree rotation of incoming light, in terms of the spatial structure of O, around the *y* axis. (*x* and *z* axes for O' in spatial structure of O, who does not wear the optical apparatus, are shown.)

simultaneously in the other situation none of the radioactive material decayed, leading to the cat being alive when observed. One situation involves the observer who has not worn the optical device and who is not wearing the device when he or she observes the electron. The other situation involves the observer who is wearing the apparatus when observing the electron and who has adapted to the rotated visual field. In contrast to the Schrodinger cat gedankenexperiment, each observer's perception is similar in structure. But while the effect of the rotation of incoming light for a subject is mitigated upon adaptation, the historical physical event of the rotation of the incoming light due to the optical apparatus remains for the observer wearing the device and acts to distinguish the two situations of the observers.

In this regard, a portion of Boring's (1929/1950) quote presented above is particularly relevant.

> [Stratton] described how up was nothing in the visual sensory pattern other than the opposite of down, and that orientation is achieved by the relation of the visual pattern to somothesis and behavior. When you reach up to get an object imaged at the top of the retina, then you have indeed got the visual field reversed and will not find the object unless you have on Stratton's lenses. (p. 678)

The world and the subject's experience of the world thus do not appear changed, unless, as the data suggest, the subject thinks about his wearing the optical apparatus and the subsequent experiential and behavioral change that accompanies the initial presentation of light to the retina after it passes through the optical apparatus.

A Possible Objection

One might object to this conclusion regarding the "righting" of the visual field for the adapted subject in the following way. The artificial reorientation of the incoming light does not prevent tracing back light impacting the retina to the physical existent that is the source of the light so that the actual spin component of the electron along a particular axis in space and the visual perceptions of the electron's spin component in space by the observer for whom light is not inverted, or otherwise rotated, and by the individual adapted to the incoming, altered light are all in agreement. That is, both observers correctly deduce the spin component of the electron because they correctly perceive the motion of the electron in space along the spatial axis along which it is traveling. Then the visual system could be said to simply adapt to the artificial change in incoming light but that the internal sensory coordination by the observer ultimately reflects the absolute positioning of the electron's motion in space as it moves through the Stern-Gerlach device.

But, consider that instead of using an external optical system to alter the orientation of incoming light, another method is used in the gedanken-experiment to change the orientation of light on the retina. Consider that the retinas of an observer with their supporting physiological structures in the eye, in particular the optic nerve, are rotated 180°. In this arrangement, an optical apparatus external to the visual system is no longer used. (Both procedures accomplish the same goal, rotation of incoming light 180° on the retina.) The results, though, of using either the external optical system or reorienting the retinas themselves should be the same. The human subject whose retinas have been reoriented should with adaptation see the world upright even though the incoming light falls on the retinas in the opposite manner to that found for the observer whose retinas have not been reoriented, where space is considered in terms of the spatial structure of this latter observer. By reorienting the retinas themselves, one can no longer reasonably subscribe to the thesis that the visual system is simply accounting for the artificial nature of the external optical apparatus in order to correctly ascertain the absolute positioning of the electron's motion in space. Here, no extra instrument is added. Only the orientation of the incoming light relative to the retina has been changed.

IMPLICATIONS FOR EINSTEIN'S GEDANKENEXPERIMENT

In Einstein's gedankenexperiment, the circumstances involving S_2 are akin to the experiment discussed above involving the spin angular momentum of an electron traveling through a nonuniform magnetic field in a Stern-Gerlach apparatus. That is, one could essentially apply the experimental arrangement discussed above, including the use of a suitable optical apparatus for the human observer, directly to S_2. One very likely would find that both wave functions in Einstein's gedankenexperiment could describe S_2 for different observers, one wearing the apparatus and the other not. In view of the results on biperceptual experience resulting from inversion of incoming visual stimuli, perhaps one would find that both wavefunctions could describe S_2 for the same observer. Thus, Einstein's result is not only the correct result theoretically in quantum mechanics, but is also subject to empirical test. Because of the results of the experiments in psychology that have been cited and because these results are concerned with adaptation to much more complex perceptual circumstances than would likely occur in the proposed experiment concerning the spin component of electrons along a spatial axis, it is expected that such an experiment would support Einstein's theoretical result that "very different" (Einstein, 1949/1969, pp. 85) wave functions can simultaneously describe the same physical circumstances in the manner described.

HOW HAS THE SIGNIFICANCE OF THE ACT OF OBSERVATION BEEN MISSED?

Why have physicists generally missed the significance of the *act* of observation, and specifically human observation, in quantum mechanics? And why have they missed the assumed anisotropy of space that is tied to the assumption of an absolute upright status of the physical world in visual perception? More practically, how, for example, could physicists at the Massachusetts Institute of Technology have missed the significance of Held's work, some of the most significant on the plasticity of perception, to their own work? Held has been on the faculty at MIT in the Department of Brain and Cognitive Sciences for many years.

In part, physicists have missed the significance of the act of observation because they have looked for consciousness, or cognition in general, to be like a physical *object* in quantum mechanics, not as an *act* for which physical objects are the objects of perception. This view of consciousness has allowed Adler (1989) to essentially propose that the discovery of the neutrino depended on a cognitive choice by physicists concerning the content of physical theory in the face of ambiguous empirical results while framing his argument in terms of general philosophical tenets instead of this cognitive choice.

> I believe there is little reason to be convinced by this experiment [the definitive experiment by Cowan, Reines, Harrison, Kruse, and McGuire (1956)] that the neutrino exists apart from the theory and experiments that define it. The theory of beta decay is embedded in the larger theory of conventional physics and the experiment is constructed according to the rules of conventional physics. The neutrino is then a necessary constituent of the theory and the associated experiment. It exists as a building block of physics, but does it necessarily exist apart from the physics that defines it--I think not! (Adler, 1989, p. 880)

Instead of discussing the cognitive framework of physicists who consider the neutrino, Adler attempted to place his view within the philosophical positions of realism, anti-realism, arealism, phenomenalism, and instrumentalism (Snyder, 1990).

As another example, consider a comment by the physical scientist Elitzur (1991) that psychology and physics "do not get along well, especially when the subject of consciousness is brought up" (p. 306) He noted that "physics sees no observable evidence for it [the existence of consciousness]" (p. 306). As represented in the Schrödinger cat gedankenexperiment or the proposed experiment involving an electron traveling through a nonuniform magnetic field, in quantum mechanics, one does not look at consciousness, or perceiving, as one looks at a physical existent. In quantum mechanics, and in experience in general, perceiving fundamentally is that through which the physical world is known. In quantum mechanics, perceiving is not an object in the same sense that a physical existent, such as an electron, is an object for observation. In obtaining empirical evidence that the predictions of quantum mechanics concerning physical existents are correct, one obtains evidence for the means in quantum mechanics through which information is gained in measurement and theoretical formulations, namely human observation and human cognition. This is what a straightforward explanation of the quantum mechanical wave function indicates. One can go further. For example, in the Schrödinger cat gedankenexperiment and the experiment proposed here, the data obtained from measurement concern physical existents. As has been shown, in manipulating how these data are received by the human observer, one can demonstrate the significance of cognition in quantum mechanics.

There is a connection between physicists in general not seeing the central role of the act of observation in quantum mechanics and their not seeing that the probabilities in quantum mechanics are fundamentally concerned with an individual's knowledge of the physical world. That physicists do not fully acknowledge that the quantum mechanical wave function provides the basis for the probabilities that are fundamentally concerned with an individual's knowledge of the physical world is tied to their failure to realize the significance of Schrödinger's gedankenexperiment as concerns the relation of the human observer to the physical world in quantum mechanics.

When a straightforward explanation of the nature of the quantum mechanical wave function is proposed to physicists, their general response, if they do respond, is that there is no new physics in the explanation, only an additional interpretation of the formalism of quantum mechanics (Elitzur, 1991). Physicists want to see new empirical results that result from a straightforward explanation of the quantum mechanical wave function. Physicists generally maintain that a new result would convince them that the wave function is an indivisible link between cognition and the physical world. In maintaining this position, physicists miss the point that empirical evidence already exists. Essentially, they are looking for an event that does *not* fit in the theory of quantum mechanics and which is also mediated by cognition. Any result that is predicted in the theory of quantum mechanics is for many physicists subject to the criticism, "There is no new empirical result."

And yet, as discussed, it is the theory of quantum mechanics itself that allows for the fundamental link between cognition and the physical world. An avenue for empirical confirmation is the one discussed above: empirical evidence is found through adjusting the variables affecting the act of perceiving and not those affecting the measured physical system itself. The data obtained in the measurement process concern quantities of the measured physical system. The expected empirical results are those predicted in quantum mechanics. Unlike the avenue outlined here, the new empirical result that physicists maintain is necessary to demonstrate a fundamental link between cognition and the physical world itself necessitates denying the fundamental validity of quantum mechanics. In a sense, physicists are asking those who propose that this link exists to demonstrate it through finding the hidden variables that would indicate that quantum mechanics is not the correct theory describing the physical world and that some form of classical-like physical theory correctly describes the physical world.

Physicists cannot expect that a new result that effectively contradicts quantum mechanics can then be used to support the thesis that the wave function is a link between cognition and the physical world. Instead, it can be expected that a cognitive component can affect how the results predicted by quantum mechanics are manifested such that the unusual nature of the results indicates that cognition does indeed play a role in quantum mechanics. It can be shown that cognition provides flexibility such that the empirical results achieved using quantum mechanics are dependent on the cognitive processes in individuals in a way that the physical world cannot mediate. This is what is at the heart of the Schrödinger cat gedankenexperiment. The experiment proposed in this paper is another attempt to demonstrate this point.

How could this stance by physicists have come about? Essentially, it resulted from the creation of the discipline of psychology in the latter 1800's as a distinct discipline, which was part of a larger pattern of differentiation of knowledge into specialty disciplines in the late 19th century. Philosophy and physical and biological science were important influences on the development of psychology as an independent discipline. The physicists Helmholtz and Fechner were particularly important in this development (Boring, 1929/1950). The experiment reported by Helmholtz above clearly had a significant psychological dimension. If his argument on the relation of vision and touch is followed a bit further, his interest and skill in exploring psychological phenomena is even more apparent:

> Here [in the experiment where an observer wears the glass prisms] it is not the muscular feeling of the hand that is at fault or the judgment of its position, but the judgment of the direction of the gaze, as is shown by the fact that, if after having become used to looking through the prisms and finding the visible objects with the right hand, then we close our eyes and try to touch the same objects with the left hand, which has not been previously used, and which was not in the field of view, we find that there will not be any difficulty about touching them with perfect certainty and precision. Accordingly, in a case of this kind the place is determined perfectly correctly, and thereafter it can be found with certainty by another organ of touch.
>
> We know by experience that children three months old are very slow in learning to point their hands toward objects they see, although they may know very well from the sensations of touch how to direct them to the mouth or to an itching place on the skin. They have to make many trials before they learn to understand the correspondence here between movement of eyes and hands; and so also even in the case of grown people the accuracy of this correspondence has to be continually regulated by constantly repeated experiments and observations. (Helmholtz, 1866/1925, pp. 246-247)

It is very difficult to imagine a contemporary physicist providing such an analysis of the relation of vision to touch in connection with the location of objects in space. If psychology had not become a discipline independent of physics and biology as well as philosophy, those scholars specializing in physical science would not expect data that contradicted quantum mechanics to demonstrate a point within quantum mechanics, namely that the wave function is a connection between cognition and the physical world. For their part, those scholars particularly knowledgeable about psychological phenomena also would have been knowledgeable enough about physics not to have let this position stand. The significance of Helmholtz's early report on the effects of altering incoming visual stimuli would not have been missed by physicists who developed quantum mechanics, and the cognitive feature of the wave function would have been recognized much sooner.

Bohr's Complementarity and Psychology

It should be pointed out that Bohr was one physicist who was familiar with psychology, and it appears that his familiarity had the greatest of consequences. Of those physicists responsible for the development of quantum mechanics, it was Bohr, who went the farthest in recognizing that psychological phenomena were part and parcel of the quantum mechanical wave function. In the mid-1920's, Bohr came to understand that in quantum mechanics, certain quantities (such as the position or momentum) of certain physical existents (such as an electron) cannot both be known with arbitrary precision. He understood that in principle descriptions of these quantities are mutually exclusive. In that the mutually exclusive descriptions of these quantities could both describe the existent and as these descriptions together could simultaneously apply to the existent in pre-quantum physics, Bohr called these descriptions complementary. Bohr anchored complementarity to the physical world because, for Bohr, the mutually exclusive descriptions were determined by the concrete experimental arrangements that the physicist had selected (e.g., one experimental arrangement to measure position and another experimental arrangement to measure momentum of an electron) (Bohr, 1935).

It appears that Bohr was significantly influenced by the psychologist William James in his development of the concept of complementarity, a central concept in the theory of quantum mechanics. Jammer (1966/1989) argued that William James' work had a significant impact on Bohr's work in physics, specifically in his development of complementarity. Jammer wrote, "Bohr repeatedly admitted how impressed he was particularly by the psychological writings of this American philosopher" (p. 182). Bohr was introduced to James' work by Höffding, who is best known in psychology for the Höffding step (Hilgard & Bower, 1975). It appears that Bohr was well-acquainted with certain ideas discussed in James' *The Principles of Psychology*.

In discussing the origin of Bohr's concept of complementarity, Jammer noted that it was probably James' use of the term in his discussion of work by Janet and others on hysteria that had the major impact on Bohr. In *The Principles of Psychology*, James (1890/1983) wrote:

> It must be admitted, therefore, that *in certain persons* [suffering from hysteria], at least, *the total possible consciousness may be split into parts which coexist but mutually ignore each other*, and share the objects of knowledge between them. More remarkable still, they are *complementary*. Give an object to one of the consciousnesses, and by that fact you remove it from the other or others. (p. 204)

Bohr seems to have suggested that complementarity itself might fundamentally involve the fundamental structuring of perception, namely the essential separation between that which is perceived and the perceiving person. In this separation only a part of the world is thus accessible to the perceiving person because this person of necessity has a particular stance in the world. Bohr (1934/1961) wrote about the fundamental structure of perception:

> For describing our mental activity [which includes perceptions of the physical world], we require, on one hand, an objectively given content to be placed in opposition to a perceiving subject, while, on the other hand, as is already implied in such an assertion, no sharp sensation between object and subject can be maintained, since the perceiving subject also belongs to our mental content. From these circumstances follows...that a complete elucidation of one and the same object may require diverse points of view which defy a unique description. (p. 96)

It appears that the inescapable interaction between the measuring apparatus and the physical entity measured that was at the heart of Bohr's response to Einstein, Podolsky, and Rosen might indeed be subsumed in the more fundamental structure of perception. Once the significance of the perceiving person to perception is acknowledged it is not very far to acknowledging that "very different" (Einstein, 1949/1969, p. 85) wave functions to which Einstein referred indicate the possibility of mutually exclusive situations simultaneously characterizing the same concrete physical circumstance is indeed what a straightforward explanation of the quantum mechanical wave function entails.

This object for the perceiving subject can of course be some psychological phenomenon. As noted, Bohr stated clearly that for physical existents, it was the unavoidable interaction of the measuring instrument with the existent measured that was the basis for complementary description. It is thus particularly interesting that in the quote immediately above, Bohr seemed to indicate that complementarity may in its essence be an issue of the nature of cognition, whether the phenomena considered are psychological or physical in nature, and that the concrete experimental arrangement that Bohr emphasized in physics may be subsumed in the more fundamental nature of cognition.

In addition, with a bit more attention to James' description of hysterics, Bohr may well have recognized that Einstein, Podolsky, and Rosen's experiment really afforded the possibility of mutually exclusive situations characterizing the same concrete physical circumstances. In the above quote from *The Principles of Psychology*, James (1890/1983) acknowledged that the hysteric manifests "possible consciousnesses...[that nonetheless may] "*coexist*....[even though you may] give an object to one of the consciousnesses, and by that fact you remove it from the other or others" (p. 204).

CONCLUSION

An experiment has been proposed in this paper that applies methodology from psychological research to an experiment in which an experimental arrangement from physics is used. Based on the results of psychological research that relied on this methodology, it is likely that Einstein, Podolsky, and Rosen's surprising theoretical result that mutually exclusive quantum mechanical wave functions can simultaneously apply to the same concrete physical circumstances can indeed be implemented on an empirical level. This conclusion lends support to the thesis that the quantum mechanical wave function is a link between human cognition and the physical world. Among other factors, this thesis results from: 1) the quantum mechanical wave function being the basis for whatever can be known concerning the physical existent with which it is associated, 2) the knowledge derived using the wave function is fundamentally probabilistic, and 3) the wave function in general changes immediately throughout space upon measurement and, thus, so do the probabilities that are dependent on it.

Using an article by Shimony, the approach of physicists to understanding the quantum mechanical wave function is discussed, and the historical basis for their approach has also been explored. A comparison of physicists' consideration of the quantum mechanical wave function was made to the behaviorists' consideration of mind earlier in this century. Of the physicists responsible for the development of quantum mechanics, it was Bohr who appears to have been the most familiar with psychology and who came the closest to recognizing that psychological phenomena were part and parcel of the quantum mechanical wave function.

There is one further note I would like to make. This note concerns the use of the Greek letter Ψ that is far and away the most common designation for the wave function in quantum mechanics. Ψ is also used by the American Psychological Association as its logo. The underlying meaning of its designation as the logo for the American Psychological Association is readily apparent to me, as is the etymological dependence of words related to the mind in English, such as psychology and psychoanalysis, upon it. The use of, and dependence on, Ψ in these cases derives from the Greek mythological character Psyche, who came to stand for the soul. Thus, the use of the symbol in psychology is not a mystery.

But the use of Ψ so prevalently in physics to represent the quantum mechanical wave function, including its use by Schrödinger in his first papers on wave mechanics (e.g., Schrödinger, 1926a/1928, 1926b/1928), is another matter. As has been discussed in this paper, early on major figures in the development of the quantum mechanics (e.g., Bohr, Schrödinger, Einstein, and Heisenberg) realized that the measurement process was central to the concept of physical reality in quantum mechanics and recognized that a link between cognition and the physical world was not an unnatural possibility in quantum mechanics, even if they maintained that it was not in fact the case.

This realization does not seem to have eluded contemporary physicists as well. For example, Mermin (1985) quoted Greenberger, a physicist who said, "Quantum mechanics is magic" (p. 38). Or Feynman (1982) wrote:

> We always have had (secret, secret, close the doors!) we always have had a great deal of difficulty understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it. And therefore,

> some of the younger students...you know how it always is, every new idea, it takes a generation or two until it becomes obvious that there's no *real* [emphasis added] problem. It has not yet become obvious to me that there's no *real* [emphasis added] problem. I cannot define the *real* [emphasis added] problem, therefore I suspect there's no *real* [emphasis added] problem, but I'm note [sic] sure there's no *real* [emphasis added] problem. (p. 471)

That Feynman (1982) cannot define the "real problem" (p. 471) and is "not sure there's no real problem" (p. 471) is the case in part because physicists have maintained a stance that does not allow for a straightforward explanation of the quantum mechanical wave function. Feynman's repeated use of the word "real" signifies his acknowledgement that the primary issue of concern to him is whether the physical world in quantum mechanics exists independently of the individual who is thinking about it and observing it.

Some of the assumptions that have hidered a straightforward explanation of the quantum mechanical wave function have been explored in this paper, and an attempt has been made to begin the reintegration of knowledge from psychology and physics. This reintegration of knowledge has provided the basis for an empirical demonstration that the quantum mechanical wave function is a link between human cognition and the physical world.

REFERENCES

Adler, C. G. (1989). Realism and/or physics. *American Journal of Physics*, *57*, 878-882.

Aspect, A., Dalibard, J., and Roger, G. (1982). Experimental test of Bell's inequalities using time-varying analyzers. *Physical Review Letters*, *49*, 1804-1807.

Aspect, A., Grangier, P., and Roger, G. (1982). Experimental realization of Einstein-Podolsky-Rosen-Bohm *gedankenexperiment*: A new violation of Bell's inequalities. *Physical Review Letters*, *49*, 91-94.

Blakeslee, S. (1993, June 1). Scanner pinpoints site of thought as brain sees or speaks. *The New York Times*, pp. B5-B6.

Blodgett, H. C. (1929). The effect of the introduction of reward upon the maze performance of rats. *University of California Publications in Psychology*, *4*, 113-134.

Bohr, N. (1935). Can quantum-mechanical description of nature be considered complete? *Physical Review*, *49*, 1804-1807.

Bohr, N. (1961). *Atomic theory and the description of nature*. Cambridge, England: Cambridge University Press. (Original work published 1934)

Boring, E. G. (1950). *A history of experimental psychology* (2nd ed.). New York: Appleton-Century Crofts. (Original work published 1929.)

Born, M. (1983). On the quantum mechanics of collisions. In J. A. Wheeler and W. H. Zurek (Eds.), *Quantum theory and measurement* (pp. 52-55). Princeton: Princeton University Press. (Original work published 1926)

Brown, G. G. (1928). Perception of depth with disoriented vision. *The British Journal of Psychology - General Section*, *19*, 117-146.

Cowan, C. L., Reines, F., Harrison, F. B., Kruse, H. W., & McGuire, A. D. (1956). Detection of the free neutrino: A confirmation. *Science*, *124*, 103-104.

Dolezal, H. (1982). *Living in a world transformed*. New York: Academic Press.

Einstein, A. (1969). Autobiographical notes. In P. A. Schilpp (Ed.), *Albert Einstein: Philosopher-scientist* (Vol. 1, pp. 1-94). La Salle, Illinois: Open Court. (Original work published 1949)

Einstein, A., Podolsky, B., and Rosen, N. (1935). Can quantum-mechanical description of physical reality be considered complete? *Physical Review*, 47, 777-780.

Eisberg, R. and Resnick, R. (1985). *Quantum physics of atoms, molecules, solids, nuclei and particles* (2nd ed.). New York: Wiley.

Elitzur, A. (1991). Neither materialism or idealism: A reply to Snyder. *The Journal of Mind and Behavior*, *12*, 303-308.

Ewert, P. W. (1930). A study of the effect of inverted retinal stimulation upon spatially coordinated behavior. *Genetic Psychology Monographs: Child Behavior, Animal Behavior, and Comparative Psychology*, *7*, 177-363.

Feynman, R. P. (1982). Simulating physics with computers. *International Journal of Theoretical Physics*, *21*, 467-488.

Gibson, J. J. (1933). Adaptation, after-effect and contrast in the perception of curved lines. *Journal of Experimental Psychology*, 16, 1-31.

Held, R. (1965). Plasticity in sensory-motor systems. *Scientific American*, *213*(5), 84-94.

Held, R. & Freedman, S. J. (1963). Plasticity in human sensorimotor control. *Science*, *142*, 455-462.

Helmholtz, H. (1925). *Helmholtz's Treatise on Physiological Optics: The Perceptions of Vision* (trans., J. P. C. Southall) (Vol. 3). Menasha, Wisconsin: Optical Society of America. (Original work published in 1866)

Hilgard, E. R., & Bower, G. H. (1975). *Theories of learning* (4th ed.). Englewood Cliffs, New Jersey: Prentice-Hall.

James, W. (1983). *The principles of psychology*. Cambridge, Massachusetts: Harvard University Press. (Original work published 1890)

Jammer, M. (1989). *The conceptual development of quantum mechanics*. New York: Tomash Publishers and American Institute of Physics. (Original work published 1966)

Kandel, E. R., Schwartz, J. H., & Jessell, T. M.. (1991). *Principles of neural science* (3rd ed.).. New York: Elsevier.

Kohler, I. (1962). Experiments with goggles. *Scientific American*, *206*(5), 62-72.

Kohler, I. (1964). The formation and transformation of the perceptual world [H. Fiss, trans.]. *Psychological Issues*, *3*, 19-133, 165-173.

Liboff, R. (1992). Introductory quantum mechanics (2nd ed.). Reading, Massachusetts: Addison-Wesley.

Mermin, N. D. (April, 1985). Is the moon there when nobody looks? Reality and the quantum theory. *Physics Today*, 38-47.

Munn, N. L. (1965). *The evolution and growth of human behavior* (2nd ed.). Boston: Houghton Mifflin. (Original work published 1955.)

Schrödinger, E. (1928). Quantisation as a problem of proper values: Part I. In E. Schrödinger, *Collected Papers on Wave Mechanics* (pp. 1-12). London: Blackie & Son. (Original work published 1926) (a)

Schrödinger, E. (1928). Quantisation as a problem of proper values: Part II. In E. Schrödinger, *Collected Papers on Wave Mechanics* (pp. 13-40). London: Blackie & Son. (Original work published 1926) (b)

Schrödinger, E. (1983). The present situation in quantum mechanics. In J. A. Wheeler and W. H. Zurek, *Quantum theory and measurement* [J. Trimmer, Trans.] (pp. 152-167). Princeton, New Jersey: Princeton University Press. (Original work published 1935)

Shimony, A. (1988). The reality of the quantum world. *Scientific American*, *258*, *1*, 46-53.

Snyder, D. M. (1986). Light as an expression of mental activity. *The Journal of Mind and Behavior*, *7*, 567-583.

Snyder, D. M. (1989). The inclusion in modern physical theory of a link between cognitive-interpretive activity and the structure and course of the physical world. *The Journal of Mind and Behavior*, *10*, 153-171.

Snyder, D. M. (1986). On the relation between psychology and physics. *The Journal of Mind and Behavior*, *11*, 1-17.

Snyder, D. M. (1990). Comment on Adler's "Realism and/or physics." *American Journal of Physics*, *58*, 520.

Snyder, F. W., & Pronko, N. H. (1952). *Vision with spatial inversion*. Witchita, Kansas: University of Witchita Press.

Snyder, F. W,, & Snyder, C. W. (1957). Vision with spatial inversion: A follow-up study. *The Psychological Record*, *7*, 21-30.

Stratton, G. A. (1896). Some preliminary experiments on vision without inversion of the retinal image. *The Psychological Review*, *4*, 611-617.

Stratton, G. A. (1897a). Vision without inversion of the retinal image - 1. *The Psychological Review*, *4*, 341-360.

Stratton, G. A. (1897b). Vision without inversion of the retinal image - 2. *The Psychological Review*, *4*, 463-481.

Tolman, E. C. (1949). *Purposive behavior in animals and men*. Berkeley: University of California Press. (Original work published 1932)

Tolman, E. C., & Honzik, C. H. (1930). Introduction and removal of reward, and maze performance in rats. *University of California Publications in Psychology*, *4*, 257-275.